SLAC-PUB-12315
hep-ex/0611029



# MEASUREMENT OF $e^+e^-$ MULTIHADRONIC CROSS SECTIONS BELOW 4.5 GeV WITH *BABAR*

Achim Denig

Representing the *BABAR* collaboration

*Institut für Experimentelle Kernphysik, Universität Karlsruhe (TH)*
*Postfach 3640, D-76021 Karlsruhe, Germany*
*E-mail: achim.denig@iekp.fzk.de*

We present a summary of the hadronic cross section measurements performed with *BABAR* at the PEP-II collider via *radiative return*. *BABAR* has performed measurements of exclusive final states containing 3, 4 and 6 hadrons via this complementary method, as well as a measurement of the proton form factor.

## 1. Initial State Radiation Physics at *BABAR*

At the particle factories DAΦNE and PEP-II the hadronic cross section $\sigma(e^+e^- \to \text{hadrons})$ is measured over a wide energy range by *radiative return*[1,2] . In this new method only those events are considered, in which one of the beam electrons or positrons has emitted an initial state radiation (ISR) photon, lowering in such a way the effective invariant mass of the hadronic system. Precision measurements of the hadronic cross section are of utmost importance since they provide input to data-driven calculations of the hadronic contributions to the anomalous magnetic moment of the muon, $a_\mu$, and of the running fine structure constant $\alpha(m_Z^2)$[3,4] . In this paper we present measurements of different exclusive final hadronic states in the mass range $< 4.5$ GeV, performed at the B-factory PEP-II ($\sqrt{s} = 10.6$ GeV) with the detector *BABAR*. At *BABAR* the ISR photon is required to be emitted at large polar angles with respect to the beam axis, allowing a kinematic closure of the event (*tagging*). Since the hadronic system is recoiling opposite to the ISR photon, a measurement of the cross sections with very high geometrical acceptance becomes possible. In order to extract the *non-radiative* cross section from the measured *radiative* cross section, one normalizes to a well-known radiator function[5] and to the PEP-II integrated luminosity, or - alternatively - to the yield of $e^+e^- \to \mu^+\mu^-\gamma$ events.

*Contributed to 5th International Workshop on Chiral Dynamics, theory and Experiment (CD 2006), 09/18/2006--9/22/2006, Durham / Chapel Hill, North Carolina*

Work supported in part by the US Department of Energy contract DE-AC02-76SF00515

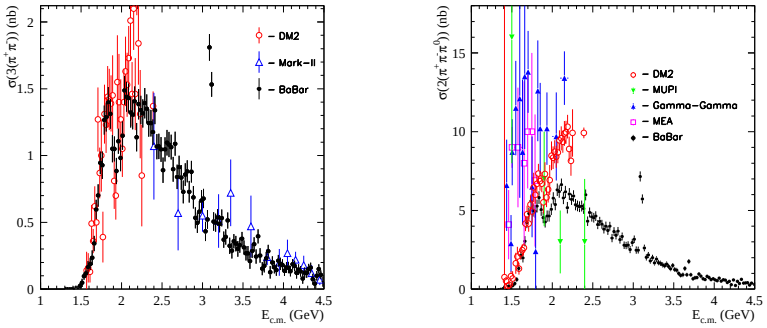


Fig. 1. The *BABAR* measurement of the cross section for $e^+e^- \to \pi^+\pi^-\pi^+\pi^-\pi^+\pi^-$ (left) and $e^+e^- \to \pi^+\pi^-\pi^+\pi^-\pi^0\pi^0$ (right) vs. $\sqrt{s}$ compared to the world data set.

## 2. Results

### Three and four hadrons

*BABAR* has previously published measurements[6,7] of the $\pi^+\pi^-\pi^0$, $\pi^+\pi^-\pi^+\pi^-$, $K^+K^-\pi^+\pi^-$, $K^+K^-K^+K^-$ final states with better precision and coverage than all previous experiments, using 89 fb$^{-1}$ of data. The systematic accuracy of the $3\pi$- and $4\pi$-channels in the mass region $1-2$ GeV is 5%. All states have been studied also in terms of their internal structures. In the $\pi^+\pi^-\pi^0$ analysis it was possible to improve significantly on the world's knowledge the excited $\omega$ states, while in the $\pi^+\pi^-\pi^+\pi^-$ channel a very strong contribution from the two-body mode $a_1(1260)\pi$ was identified. Preliminary results from a data sample of 232 fb$^{-1}$ are available for the $e^+e^- \to K^+K^-\pi^+\pi^-$ and $K^+K^-\pi^0\pi^0$ cross section[8] . In the $\phi(1020)f_0(980)$ intermediate two-body state a vector resonance-like structure is seen near threshold with a mass of $(2175 \pm 10_{\rm stat} \pm 15_{\rm syst})$ MeV and a width of $(58 \pm 16_{\rm stat} \pm 20_{\rm syst})$ MeV.

### Six hadrons

The six-hadron process[9] has been studied in a data sample of 232 fb$^{-1}$ in the channels $e^+e^- \to 3(\pi^+\pi^-), 2(\pi^+\pi^-\pi^0)$ and $2(\pi^+\pi^-)K^+K^-$. The cross sections for the first two channels are shown in fig. 1; large improvements over existing measurements are seen, as well as a much wider coverage of the mass range. In the all-charged mode very little substructures have been found; a simulation containing one $\rho^0$ and four pions distributed according to phase space is adequate to describe the internal structure. On the contrary the partly neutral state shows a much more complex structure with

signals for $\rho^0, \rho^\pm, \omega$ and $\eta$, and a substantial contribution from $\omega\eta$, which seems to be resonant. In both channels a structure at ca. 1900 MeV, which had previously been seen by DM2 and FOCUS[10] , is clearly visible. Fits to the $3(\pi^+\pi^-)$ and $2(\pi^+\pi^-\pi^0)$ spectra, assuming a resonant structure over a continuum shape, give consistent results for the mass $M$ and width $\Gamma$ of the structure. For the channel $3(\pi^+\pi^-)$ we find $M = (1880 \pm 30)$ MeV and $\Gamma = (130 \pm 30)$ MeV, for the channel $2(\pi^+\pi^-\pi^0)$ $M = (1860 \pm 20)$ MeV and $\Gamma = (160 \pm 20)$ MeV.

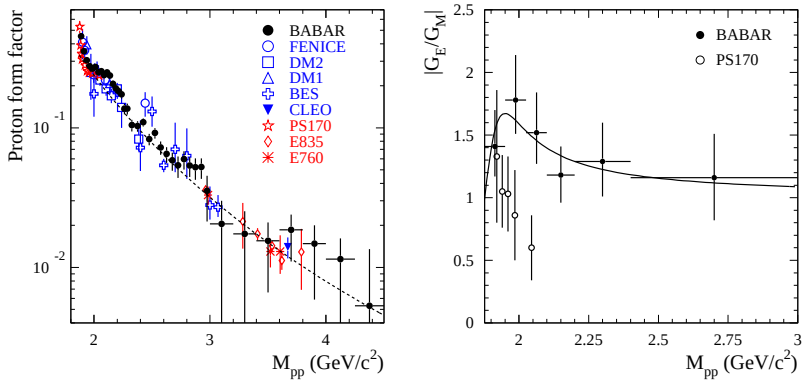


Fig. 2. Left: The *BABAR* measurement of the effective proton form factor and previous data obtained in $e^+e^-$ and $p\bar{p}$ experiments. Right: The ratio of the electric and magnetic form factor $|G_E/G_M|$ as a function of $\sqrt{s}$.

## Proton form factor

*BABAR* has also measured the cross section $e^+e^- \to p\bar{p}$ using 240 fb$^{-1}$ of data[11] ; the corresponding effective form factor is shown in fig. 2 (left), along with previous data from $e^+e^-$ and $p\bar{p}$ experiments. We find an overall good consistency. The mass dependence shows a significant threshold enhancement, as well as two structures featuring sharp drops at 2.25 and 3.0 GeV, which illustrate the power of data from one single experiment over a wide range with no point-to-point uncertainties. Measuring the proton helicity angle $\theta_P$ in the $p\bar{p}$ rest frame, one can separate the ratio of the electric and magnetic form factor $|G_E/G_M|$, since both show a different functional behaviour in $\theta_P$. The *BABAR* measurement of this ratio is shown in fig. 2 (right) for six different mass bins of $M_{p\bar{p}}$; a previous LEAR measurement[12] is in disagreement with *BABAR*. Our data shows a significant increase of the

ratio $|G_E/G_M|$ towards threshold, while the two form factors are consistent at larger masses.

## 3. Conclusions

Measurements of the hadronic cross section at PEP-II have improved the knowledge of the hadronic spectrum above 1 GeV. Thanks to the ISR-method, for the first time it becomes possible to cover the entire mass range of interest from threshold to 4.5 GeV in one single experiment. *BABAR* has not only performed precision measurements for exclusive hadronic states containing proton-antiproton, 3 pions and 4 and 6 hadrons, but has also measured 16 $J/\psi$ and $\psi(2S)$ branching ratios, out of which 10 are better than world average. Ongoing analyses are measuring the final states $\pi^+\pi^-$, $K^+K^-$, $\pi^+\pi^-\pi^0\pi^0$ and many more channels, which will further improve the standard model predictions for the muon anomaly $a_\mu$ and for the running fine structure constant $\alpha(m_Z^2)$.

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